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ABSTRACT

Described are technological considerations affecting storage of energy, particularly electrical energy. The background and present status of energy storage by batteries, water storage, compressed air storage, flywheels, magnetic storage, hydrogen storage, and thermal storage are discussed followed by a review of development trends. Included are diagrams illustrating the basic mechanisms of each storage system and energy flow diagrams for 1970 and 1985. (SL)

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Energy Storage

by William W. Eaton

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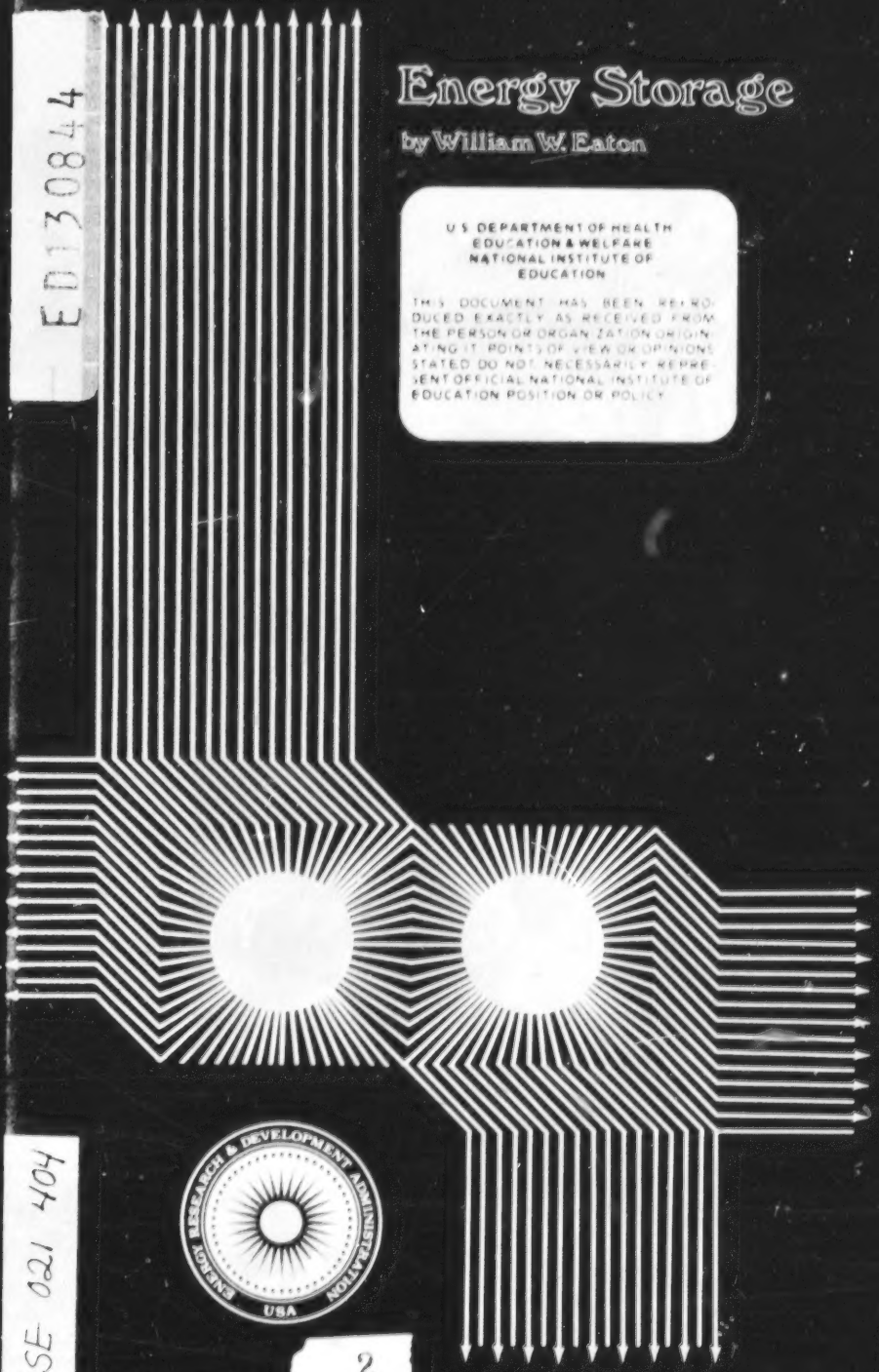

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2

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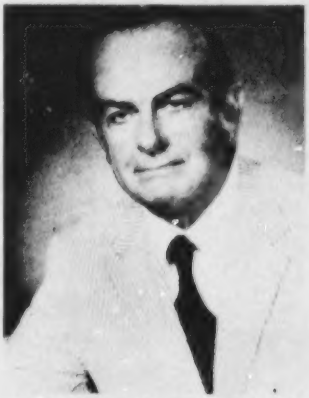

Dr. William W. Eaton, an independent consultant, holds a Ph.D. in physics from Yale University and is a registered Professional Engineer. He has extensive experience in industrial research and development, both in this country and abroad, and has been a Director or Trustee of numerous science-oriented organizations. He was closely involved with early applications of high-speed computers to problems of government and business.

For 3 years he served as Deputy Assistant Secretary for Science and Technology in the U. S. Department of Commerce. He has also been prominent in science affairs in Maryland. He headed formal studies on the environmental effects of nuclear power plants, both for the Governor of Maryland and for the Southern Governors' Conference.

Dr. Eaton has prepared patents and articles in a number of technical fields, including several related to various aspects of energy. In addition to this booklet he has written *Solar Energy*, *Energy Technology*, and *Geothermal Energy*.

Energy Storage

by William W. Eaton

Chapter I Introduction 1

Chapter II Storage of Energy and Electricity 6
- Batteries 6
- Water Storage 13
- Compressed Air Storage 14
- Flywheels 15
- Magnetic Energy Storage 19
- Hydrogen Storage 22
- Thermal Storage 26

Chapter III The Future of Energy Storage 28

Bibliography 34

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Chapter I
Introduction

Energy—the capacity to perform work—exists in several different forms. These are mainly mechanical motion, heat, and electricity, which can be converted back and forth from one into another.

The energy of motion possessed by a moving vehicle, a pile driver, or falling water, can accomplish work by producing mechanical forces directly on some other object.

The energy contained in a quantity of heat, besides being useful for many direct heating applications, can also be transformed into mechanical work through engines or turbines.

Electricity—an intermediate and intangible form of energy—can be better described by what it does rather than by what it is. The basic advantages of electricity are that it can be efficiently *transmitted* and then conveniently *transformed* into the kind of energy desired at the exact location it is needed.

For example, electricity can be carried hundreds of miles through high-tension transmission lines to homes, offices, and factories in distant cities, villages, and farms. Electricity can, by the flick of a switch, be put to work in hundreds of different ways.

Before the means to generate and transmit electricity in large quantities was discovered about 80 years ago, there was no comparable method of conveniently making energy available to the average home or office.

For example, prior to the availability of electricity, there were no electric lights, vacuum cleaners, clothes and dish

washers, electric refrigerators, air conditioners, and scores of other convenience appliances and devices that we take for granted today. Most of the physical work now done by electricity was performed by hand labor, often under conditions of time-consuming drudgery.

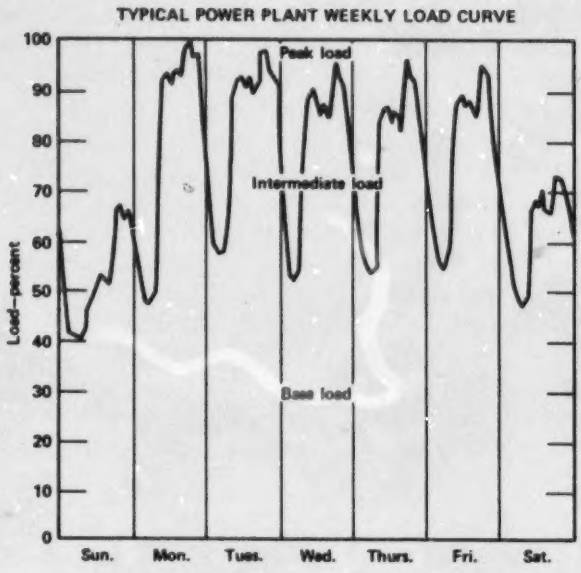
The U. S. Government, working closely with American industry, has for decades sponsored and promoted the steady expansion of electric power generation and its wide distribution in an effort to provide the energy needed to improve the quality of life.

It is significant that the total amount of electric power generated in the U.S. has doubled every decade for more than a half century. The U.S. has 6% of the world's population, but uses 33% of its electricity. More than 98% of U.S. farms are electrified. Furthermore, the cost of electricity has, until recently, dropped steadily during this long period of rapid growth.

With a total electrical capacity of roughly 0.4 billion kilowatts, and over 200,000,000 people, our country now has available, on the average, about 2 kilowatts of electric power for every man, woman, and child. This is roughly the equivalent of 3 horsepower, or the effort that can be exerted by 15–20 men.

Almost to the end of the 19th century, electricity was provided by batteries and was used mainly for such limited (though valuable) applications as the telegraph and telephone. Although many important specialized functions are still performed by batteries, the bulk of our electric power is now generated either by steam-electric plants fired by fossil fuels—coal, oil, and gas—or by hydroelectric facilities and nuclear power plants.

As man ventured into space, solar cells, which transform sunlight directly into electricity, have become essential features of most space vehicles. There is every indication, too, that if the cost of such devices could be drastically reduced, they would have important applications on earth to generate large quantities of electricity from sunlight on a local basis. Research aimed at achieving that cost reduction is now under way.



The advantages of electricity as a convenient low cost form of energy are dramatically evident at the time of an electrical blackout. One of the principal problems in the distribution of large quantities of electricity is the lack of satisfactory storage methods so that enough electricity will be available at times of peak demand without the need to install a total capacity to meet the highest load levels.

The figure above shows the typical fluctuation in demand experienced over a week's time by an electric utility network. Without a storage capability, or means of "load leveling" as it is called, the mechanical generation of power must vary in accordance with the load at any particular time. This leads to an inefficient type of steam plant operation, since these installations operate best near their full capacity. In the past, the problem has been handled, not too satisfactorily, by adding more generating capacity to the network at times of heavy demand. Most of this supplementary capacity consists now of gas turbines, which are much less efficient than the central generating plants and use scarce petroleum fuels.

In addition to the electric utility application, there are many other ways in which energy storage is important. In fact, the development of new techniques in this field has recently been recognized by both Government and industry as a vital component of an expanded national effort to broaden our energy technology base.

For example, success in this field will have a significant impact on transportation systems, such as increased use of electric vehicles, and will help to reduce the need for petroleum products by shifting to more plentiful coal and uranium to generate the electricity needed. There will also be some welcome side benefits in environmental improvement.

Full utilization of the vast amounts of solar and wind power cannot be achieved without greatly improved storage capabilities to bridge the gap between the availability of the energy sources and the time the energy is actually needed.

Efficient storage of energy either in the form of heat or electricity would be of great value in household heating applications, such as space and hot water heating, and for various commercial and industrial applications as well.

The purpose of this booklet is to present basic information about present and proposed techniques of improving energy storage to meet constantly increasing demands from the public for more power.

Chapter II outlines the background and present status of some of the proposed methods, which are being investigated, for storing energy in large quantities. The energy stored may be in electrical or other forms that can later be converted to electricity.

In chapter III, there is a general discussion of the trend in the developed countries of the world toward a greater use of electricity, which, in its later stages, might be appropriately called the "electric economy".

The damming of water for hydroelectric power generation was the first effective method of storing large amounts of energy in a form readily transformable into electricity to meet varying demands.

9

Chapter II
Storage of Energy and Electricity

Batteries

The battery, which was originally developed by Alessandro Volta around 1800, is a device for transforming the energy of certain chemical reactions directly into electricity. In its simplest form it consists of two dissimilar electrodes (electric conductors) separated by a suitable chemical substance, called the electrolyte, which is usually dissolved in water.

The chemical action, caused by the three basic components of a battery, forms an electrical voltage between the two electrodes that will produce a flow of current if placed in an electrical circuit.

For practical purposes, batteries are divided into two main classes:

1. Primary batteries, which are normally used until the chemical reactions that produce the electricity have been exhausted and cannot be reversed; and

2. Secondary, or storage, batteries, which, in addition to furnishing electric current when connected in electric circuits, can be repeatedly recharged by reversing the normal current flow, thus restoring the energy of the system so that it can be used again to produce electricity.

An example of a primary battery is the ordinary dry cell, which provides about 1½ volts and is used, until exhausted, for operating flashlights and many other electrical devices.

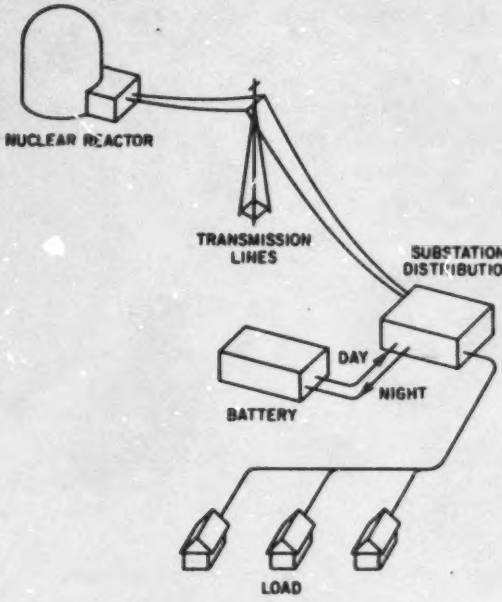
The most familiar example of a storage battery is the automotive type, which usually consists of 3 or 6 cells in

Alessandro Volta.

series that provide 6 or 12 volts respectively; these are used mainly to start the car and provide lighting.

Energy is removed if the battery in a car is used while the engine is not running. After the motor starts, the battery is normally charged by a generator that forces current back through the cells in the opposite direction; this reverses the chemical reactions, and, in effect, produces the capability for furnishing additional electrical energy for future use. Besides automotive batteries, there are other types of storage batteries that are used for a variety of purposes.

A storage battery is a relatively efficient way of storing energy. The overall process yields about 70% of the electricity originally put into the battery. However, the most challenging technical problem is to achieve substantial increases in the quantities of electrical energy that can be stored per unit weight of the battery. If such improvements could be achieved, the consequences would be very significant for many different applications.



This drawing shows how batteries are incorporated into a utility network for storage of off-peak energy. The batteries are recharged during periods of low demand and discharged during periods of high demand.

For instance, if we had large storage batteries that could store millions of kilowatt hours of electrical energy in a manageable weight and volume, they could be effectively used with central steam-electric generating plants to assist in meeting the peak demands of an electric utility network.

During times of lower demand, a portion of the power from the base-load plants, operating at their peak efficiencies, would be used to charge batteries located at various strategic points within the network. This type of arrangement would reduce the size and cost of the central generating plants required to meet anticipated peak loads, and it would also lower transmission line costs, which represent a large portion of utility investments.

Improved storage batteries would have a variety of other very important applications. One of these would be the electric car, which, if based on a battery of 500 pounds and a storage capacity of 70 watt-hours per pound, for example, would be capable of providing a 3000-pound car with a range of 100 miles. It is estimated that such a vehicle might well

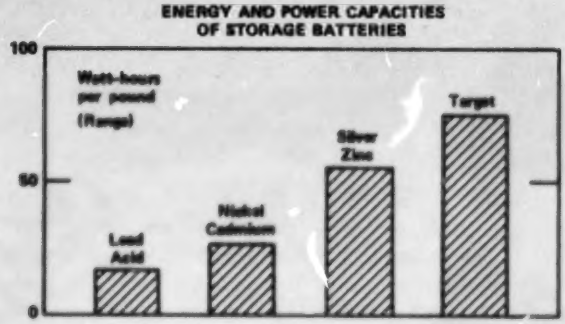
account for 20% of new car sales and 10% of all vehicles on the road by the year 2000.

The capacity for storing total electric energy, measured in watt-hours per pound of battery weight, is the most important factor in determining the maximum range of an electric vehicle as well as in measuring the usefulness of storage batteries for utility load-leveling applications.

For an electric vehicle, however, there is an additional important characteristic, which is the amount of power available when needed, or the maximum rate at which energy can be withdrawn, per pound of battery weight. This is the factor that determines acceleration of the vehicle, and it is estimated that it should have a minimum value of 100 watts per pound in order to make possible an electric car with an acceptable performance for modern highway driving.

The bar charts in the figure on pages 10 and 11 summarize the energy storage and power storage capabilities of the lead-acid battery (now used in automobiles) and some other battery systems available at higher cost. Also shown are

Below are some early versions of electric cars in 1910 in Bridgeport, Connecticut.



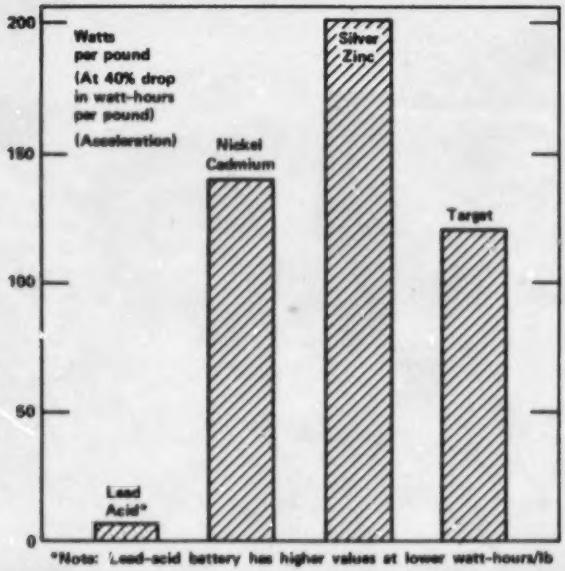
Energy and power capacities of several different storage battery systems compared to target values. Chart above shows watt-hours per pound, which largely determines maximum range in automotive applications. Chart at right indicates watts per pound under specified conditions. This characteristic is related to acceleration in the case of electric vehicles.

the goals of present research and development programs now under way to broaden the usefulness of storage batteries generally.

Some of the more promising types of new battery systems, under study by industry and by the Energy Research and Development Administration's Argonne National Laboratory near Chicago, Illinois, are based on chemical systems that must be operated at relatively high temperatures—575°–750°F (300°–400°C).

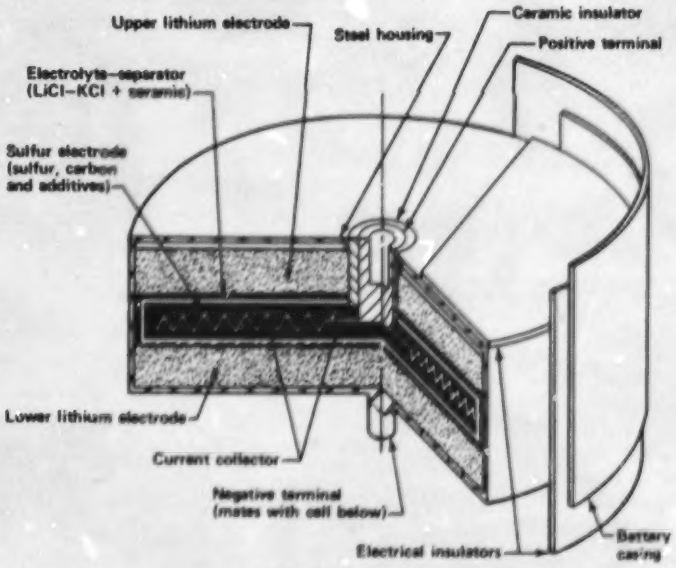
Such temperature conditions impose severe operating, sealing, and corrosion prevention requirements on batteries of this kind, but the results to date are promising.

One system being extensively examined consists of molten sodium and sulfur electrodes with a solid ceramic electrolyte. Another design is a lithium-sulfur cell that has a molten electrolyte. This system, shown in the figure on page 12, requires a slightly higher temperature than the sodium-sulfur design but theoretically has better performance characteristics.

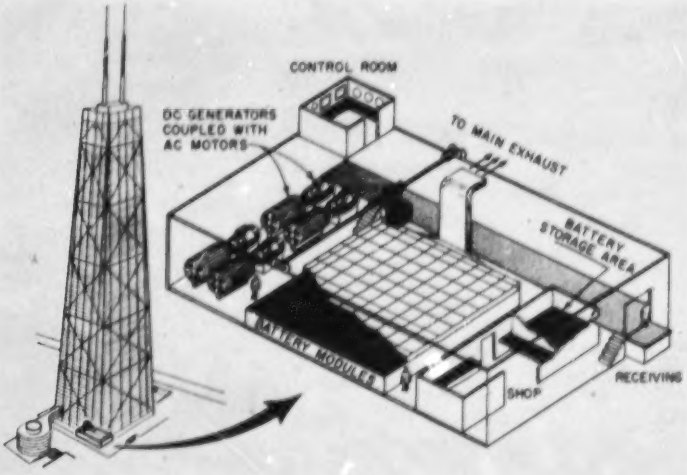


In addition to electric vehicles and peak load applications for power plants as described above, there are other important applications for improved storage batteries that, among other things, could have a profound influence on the better use of solar energy, directly and indirectly.

Assuming that solar cells, which convert sunlight directly into electricity, were available at reasonable cost, they could be widely used on individual buildings or residences to generate enough total electricity over a year's time to meet the power needs of the building. But the problem with such an application today, in addition to high cost, is that there is no satisfactory way of storing the electricity generated during periods of high sunlight intensity and warm weather for use at night and during extensive cloudy and cold periods. A significantly improved storage battery would make this important kind of energy use a reality from a technical standpoint.



The lithium-sulfur battery cell (above) produces a large amount of energy per unit weight and size. These cells can be stacked to propel an electric vehicle or for energy storage by a utility. For off-peak energy storage, large banks of batteries in an electric utility system would be charged during periods of low demand, and discharged during periods of high demand, thus leveling the load on the power generating facilities. Below is a conceptual 100 megawatt-hour lithium-sulfur battery facility.



An efficient high-capacity compact storage battery would also make it much more attractive to use windmills once again to draw upon the vast but variable energy of the winds, which are an indirect result of the sun's heat. Windmill batteries would be charged while the wind was blowing, and would supply energy during periods of calm.

A substantial breakthrough in storage battery improvement would definitely be an important key to unlock the potential for more effective use of a whole series of important electric power applications. These include utility load leveling, electric vehicles, and solar energy use. In many ways, research and development efforts along this line offer a more rewarding payoff than any other energy-related technical program now under way.

Water Storage

The damming of water for hydroelectric power generation was historically the first effective method of storing large amounts of energy in a form readily transformable into electricity to meet varying demands.

Some of these installations, when connected into an electric utility network, can also operate to assist in load leveling. Under conditions of low demand, electricity from other plants in the system is used to pump water back up behind the dam. This is available subsequently to generate electricity and assist in meeting peak loads.

The term "pumped storage" usually applies more specifically to the combination of a single steam-electric power plant (located near a water supply), a specially constructed reservoir at a higher level, and a hydroelectric generating facility that can also be operated to pump water back up into the reservoir for later use to generate electricity.

An important additional advantage of a pumped storage installation or any other energy storage method is that it makes large, high-capital-cost electric plants now being built more economically attractive. This is especially applicable to

those built near nuclear plants because the availability of the pumped storage feature makes it possible to run such plants continuously near their highest capacity, which is the most economic.

Pumped storage, first introduced in the U.S. in Connecticut in the 1930s, is still the only really effective and economic storage technique the utilities have today, and they are building additional installations wherever possible.

The overall efficiency of pumped storage installation is about 66% (2 watt-hours of output for every 3 watt-hours used to pump the water uphill). This efficiency rate is higher than other available methods used to meet the peak load problem, such as using older less efficient steam plants or additional gas turbines.

The principal disadvantages of the pumped storage scheme are the limited number of locations with suitable terrain, the long time required for the construction of the facility, and the environmental impact of such installations.

Compressed Air Storage

The idea of using compressed air as a means of storing electric energy has not yet been put into actual practice, but it is an appealing concept. Definitive application plans are under way in Europe. The proposed method is related to the widespread electric utility procedure of using gas turbine generators to assist in meeting peak load demands.

About two-thirds of the power output of the turbine is expended in operating the air compressor element that is required to obtain proper combustion. If, however, a large quantity of air could be compressed by a motor-compressor unit during off-peak periods, this compressed air could later be fed directly to the turbine generator to meet peak demands. The result would be an efficiency boost in turbine operation by 300%.

The compressed air might be stored in large naturally occurring caverns, porous ground reservoirs, or depleted gas or oil fields. Alternatively, man-made caverns, such as

exhausted salt caverns, abandoned mines, or well casings, could be used. Considerable geological work is needed to identify the availability and characteristics of suitable sites. Although specially mined caverns could be constructed and might have some operational advantages, these would represent higher capital costs than natural caverns.

Since the air may be compressed to as much as 600 pounds per square inch, the size of the storage cavern would only need to be a small fraction of the volume of water needed in a hydraulic pumped storage reservoir.

It is generally believed that the required technology exists to implement the compressed air storage scheme in the foreseeable future if proper site selection and engineering studies can be accomplished. This is the direction in which current development work is proceeding.

Flywheels

If mechanical energy is used to start any kind of a wheel rotating on its axis, the energy is in effect "stored" in the wheel. This energy remains until it is dissipated by friction forces, or until it is withdrawn from the shaft as work, thus slowing down the wheel's rotation. A wheel that can absorb, store, and give up energy in this manner is called a "flywheel".

The basic idea of using such a flywheel to meet and "even out" variable power requirements in a mechanical system is undoubtedly as old as the wheel itself. This is one of the principal functions of the potter's wheel. Early steam engines also used this principle to smooth out the power available from a single cylinder.

Most internal combustion engines, particularly those with a small number of cylinders, operate more evenly with a substantial flywheel, which stores the energy supplied intermittently by explosions in the cylinders. A good example is the now outmoded one-cylinder engine rig used on farms for a variety of jobs.

A more modern illustration is a large dragline power shovel that can meet peak requirements of up to 50,000 kilowatts by using large flywheels and has a basic power capacity of only 6000 kilowatts.

The concept of using flywheels to store energy is thus far from new in principle. However, it is currently undergoing something of a revolution (no pun intended) because of the many different requirements for electrical energy storage, the availability of new technologies, and the development of new materials.

The basic principle is that a rotating wheel represents stored mechanical (or kinetic) energy; the amount of this energy depends on its weight and its speed of rotation. Additional energy can be stored by speeding up the wheel and is withdrawn as the wheel is coupled to provide power, thus slowing down the rotation.

In figuring how much energy can be stored in a particular flywheel, the speed of rotation is more significant than the weight. For instance, if one flywheel is rotating at twice the speed of another of identical shape and weight, it contains *four* times the energy stored in the slower wheel, rather than twice as much.

In addition to air- and bearing-friction problems, high speed causes large centrifugal forces that tend to make the wheel fly apart and become a safety hazard.

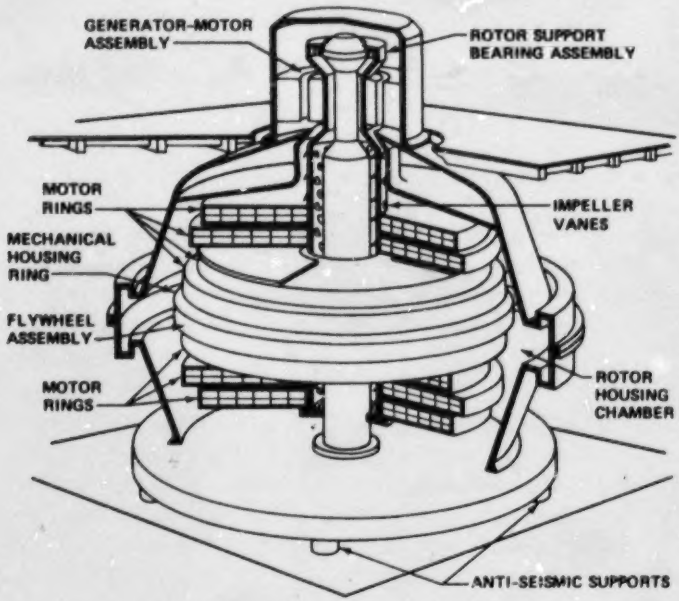
The net result of these considerations has been the recent design of new shapes, materials, and fabrication methods for flywheels so that as much energy as possible can be stored without danger.

One design of interest is the fanned brush that uses long thin fibers of various materials, such as steel wires, fiber glass, and other filaments, that have unusually high-strength properties in the long dimension.

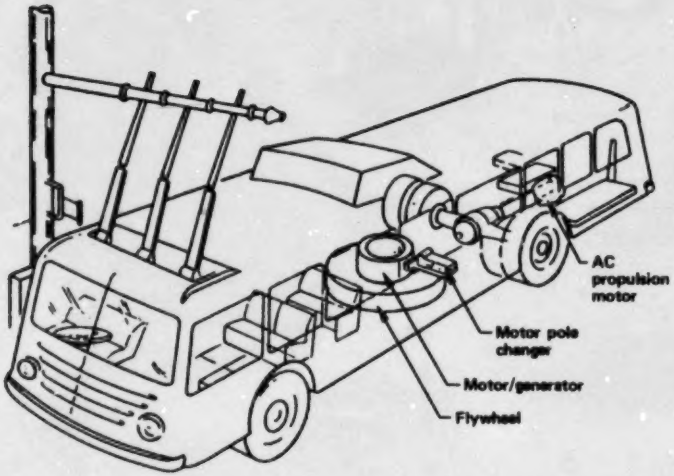
Another design takes advantage of newly developed high-strength materials in a different way. This concept is based on concentric rings of strong fiber composites separated by small gaps filled with bonded resilient material. This minimizes radial stresses that tend to cause the wheel to fail at high speeds.

The advantages of these "superflywheels" for storage of electrical energy are that they are 70%–80% efficient and could be placed conveniently close to points of heavy load demand.

As in other storage techniques applicable to the electric utility industry, power would be used to speed up the flywheels during low-load periods, and the stored energy would be subsequently used to drive generators at times of peak load demands.



This peak power unit would store energy from an electric power plant during off-peak hours and would generate energy at times of peak load. The fiber composite flywheel would be about 15 feet in diameter and weigh about 200 tons. It would be coupled to a generator-motor that would function as a motor when the flywheel was being spun up to store energy and as a generator when the system was drawing on the flywheel's stored energy.



The first commercial vehicular use for a flywheel was a gyrobus that was used both in Switzerland and the Belgian Congo. Basically, the gyrobus drew electric power from an overhead pole to spin up a flywheel. In turn, the flywheel drove a generator that powered the road wheel motors. The "refuelling" poles were spaced about a half-mile apart, and the bus was required to stop at each pole. The vehicle itself was 35 feet long, weighed 24,000 pounds, and was designed for 35 seated and 35 standing passengers.

Present calculations indicate that superflywheels can be built with much greater storage capacity per pound than, for example, presently available lead-acid storage batteries. Materials testing is under way and will be followed by construction and testing of models. If successful, expanded research and development programs and larger models would then be undertaken. A proposed design of a large load-leveling flywheel unit is shown in the figure on page 17.

Powering vehicles with flywheels is not an entirely new idea, but to date all such designs have used wheels of steel. Several years ago Swiss engineers developed a bus that used flywheel power between stops, where trolley wires provided electric power to speed up, or "charge", the flywheel by a motor. This arrangement is shown in the figure. Similar

buses, which will have flywheels of new design, are now being developed for San Francisco, and prototype subway cars using flywheels are being tested for New York City.

It is difficult at this early stage of such a new technology to evaluate the full potential for using flywheels to power automobiles. Many of the same advantages would be obtained as in battery operated vehicles, such as low pollution, high efficiency, and less use of fossil fuels. More development and experimental work appears amply justified at this time in order to reinforce the calculations that show promise for the future.

Magnetic Energy Storage

Energy can be stored in the familiar electromagnet, which consists of either an iron cylinder or a torus (doughnut shape) wound with conducting wires carrying electric current. Under ordinary conditions energy must be continuously supplied to the windings because of resistance losses. However, at very low temperatures (near absolute zero) certain conductors lose all electrical resistance to direct currents; this characteristic is called superconductivity. Once started at such temperatures, a direct current will persist indefinitely and maintain the magnetic field for possible future energy withdrawal.

The efficiency with which stored energy can be recovered in such a system is very high—about 95%—which is one of the main advantages of the concept for large-scale electricity storage.

Although only small laboratory versions of these superconducting magnets have been built for storage purposes, the idea has been studied by several research groups. It has been tentatively concluded that the use of the technique as a practical means for load-leveling assistance to utilities would be economically feasible only in very large sizes. The optimum storage size range would be 1000–10,000 megawatt* hours of electricity. This is the amount of energy

*A megawatt is 1,000,000 watts of electricity.

generated by a 1000-megawatt plant running for a period between 1 and 10 hours. Such a plant could serve a city of about 600,000 people.

The size of a magnet that could store this large amount of electric energy is impressive. It would be in the shape of a cylinder with a diameter of 50 feet, including the windings, and a height of about 50 feet. Firm placement in bedrock or other strong mounting would be necessary in order to resist the large forces on the conductor windings. The density of energy storage, or capacity per unit weight, is relatively low; hence the technique would not be practical for vehicles.

The largest superconducting magnets now in use were built for a different application, but they illustrate the principles involved. One located in Geneva, Switzerland, has a storage capacity of about 220 kilowatt-hours; this is enough to operate 200 kitchen toasters for 1 hour. A model in the shape of a torus is now planned at ERDA's Los Alamos Scientific Laboratory in New Mexico and will have a 30 kilowatt-hour capacity.

In addition to a high efficiency rating, superconducting magnetic storage devices would have the advantage of only minor environmental impacts, particularly if located underground.

On the negative side, systems for maintaining the required low temperature are expensive to construct and operate.

In summary, the outlook at this time is basically promising, but the concept is not yet ready for significant use in the near future.

Scientists at ERDA's Los Alamos Scientific Laboratory in New Mexico measure the room temperature resistance of superconducting coils and magnet suspended below thermal insulating baffles before conducting an experiment involving research into the potential of superconducting magnetic energy storage. When this unit is submersed in a dewar of liquid helium and current is passed through the conductors, they will carry between 50 and 100 amperes because they lose their electrical resistance. At room temperatures the same coils would carry only 1 or 2 amperes.

Hydrogen Storage

Hydrogen, the lightest of all the basic chemical elements of the earth, is an essential component of water and all organic life, but it is extremely rare in its elemental gaseous form.

At ordinary temperatures, hydrogen is a colorless, odorless, tasteless, and transparent gas that weighs only 7% as much as air. It is easily ignited and burns readily.

In many ways hydrogen is an ideal fuel. When burned with oxygen alone, the only product is pure water. Combustion in ordinary air yields, in addition to water, only a low concentration of nitrogen oxide pollutants, which are less than those generated by the combustion of most other fuels.

The energy content of hydrogen burned as a fuel is less than one-third that of natural gas, but its low viscosity allows it to flow much more readily than gas in pipelines.

The energy content per pound of liquid hydrogen, on the other hand, is almost three times that of hydrocarbon fuels, so it is ideal for rockets and airplanes.

Hydrogen is not a primary energy source because large amounts of energy are required to produce it; for example, by the electrical decomposition of water, called electrolysis. But hydrogen does offer promise of being a unique and efficient means of storing energy—including electricity—particularly in situations where electricity storage is inefficient or impractical.

It is the unique combination of these characteristics—(1) energy storage and carrying capacity, (2) flexibility as a fuel, and (3) potential for reconversion to electricity—combined with the projected large increase in nuclear reactors that has led to recent widespread interest in what is called the "hydrogen economy". This refers to the general use of hydrogen for a variety of applications.

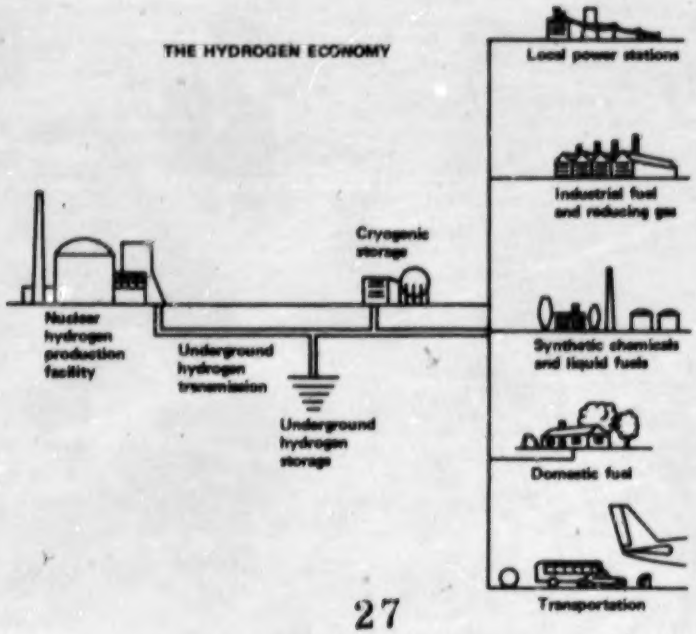
On a less complete basis, however, it is possible to visualize a useful role for hydrogen as an electricity storage medium for utility load leveling and as a fuel for vehicles in order to reduce the demand for the earth's limited supplies of petroleum.

Conventional automobile engines require only minor modifications to run on hydrogen instead of gasoline. Furthermore, the engines powered by hydrogen are likely to be more efficient and less polluting.

The major difficulty with using hydrogen in an automobile is to store enough of it to provide a reasonable operating range. However, the new storage techniques described below offer some promise of a solution to this problem.

Hydrogen can be transported and distributed in pipelines in the same manner as natural gas. The technologies for storing hydrogen as a high-pressure gas, or as a low-temperature liquid, are also well developed. For example, large-scale liquid hydrogen storage facilities have been built in connection with the space program.

An entirely different method of storing hydrogen is now being developed. It is based on a process whereby pressurized hydrogen gas diffuses into certain metals, for example, iron-titanium alloys, to produce a metal hydride



27

compound. Subsequently, when hydrogen gas is desired, heat is applied to the metal hydride and the hydrogen is released.

This method could be used in conjunction with an electric power plant if electricity generated during off-peak hours were used to produce hydrogen by the electrolysis of water and then stored as metal hydrides. The hydrogen would be withdrawn later to help meet peak demands through reconversion to electricity in fuel cells. The technical feasibility of the method has already been established and an ERDA development program is now under way that will lead to construction of a pilot plant.

Still another method of producing and distributing hydrogen is being studied in Europe. This involves chemical storage of large quantities of heat produced by nuclear or other sources. The energy would be stored by creating a heat-absorbing chemical reaction and then distributing the end products of the reaction via pipelines to the demand points. When energy is needed, the reverse chemical reaction would be created and large amounts of heat would be emitted. The original chemical components of the system would then either be returned to the basic central heat source to start the cycle all over again or could be burned as a fuel in open combustion.

This type of chemical storage technique, although still in the early stages of development, appears to offer some important basic advantages, such as adaptability to various types of heat sources, ease of transportation, low storage cost, and flexibility of end use.

Fuel cells, which generate electricity in somewhat the same manner as batteries, have been known as a scientific curiosity since 1839. Recently they have assumed an important role in the space program, but their cost is still high, they are short-lived, and their efficiency is a relatively low 40%. Hydrogen fuel cell operation can be visualized as something like electrolysis in reverse.

Another method for using hydrogen to generate electricity is to burn it as a fuel in a high-temperature gas turbine, but such a process is also seriously limited in reaching acceptable efficiencies.

The overall outlook for hydrogen as a means of indirectly storing and transmitting electric energy depends on the outcome of continued development and pilot plant demonstration work. The possibility of full-scale use is still a considerable number of years away.

Thermal Storage

Storing energy as heat offers opportunities for many different applications but presents difficult problems such as insulation, space requirements, and selection of suitable materials.

One thermal storage method already in use is the heating and storage of quantities of household hot water by using off-peak electrical power at reduced cost. The extension of this concept to space heating applications would be logical if sufficient heat could be stored economically.

A heat storage method often considered for solar-heated buildings is the use of a selected substance that is a solid at room temperature and a liquid at the temperature (120–150°F [50–65°C] or higher) of solar-heated water. The amount of stored heat given off when the heated liquid material cools and solidifies—the latent heat of fusion—is many times what would be emitted if the material remained a liquid as it cooled. Such heat could be used for hot water and space heating.

In addition to heat storage, there also is a need for cold storage to air-condition buildings, for example, or to refrigerate rooms that preserve food. By extracting the heat from a storage medium (i.e., a water tank or a rock bed), one can store the cold for use at a later date.

In today's power-hungry world, rapidly increasing quantities of low-grade heat are given off by steam-electric power plants. Such heat loss is inherent in the transformation of the heat energy of steam into the mechanical forces that operate the turboelectric generators. Unfortunately, it is now largely wasted.

If this vast amount of heat, sometimes called "thermal pollution", could be transmitted and stored efficiently, there would be many ways in which it could be used advantageously in residential, commercial, agricultural, and industrial applications. Some of these uses are already being tested.

Likewise, there would be many applications for the efficient storage of geothermal heat—the natural internal

heat of the earth—in the various geographical areas where it is available.

Further detailed analysis of the economic and technical aspects of thermal storage methods is required, however, before any significant new programs are undertaken.

Chapter III
The Future of Energy Storage

The overall pattern of energy flow in the U. S. in 1970, and as projected for 1985, is shown vividly in the figures. Since the elements of these two charts are drawn to the same scale, it is easy to get a picture of the total increase in energy utilization (about 70%) expected during the 15-year period as well as the many changes in individual input components and output applications.

U. S. electrical power consumption has been doubling every 10 years for the last half-century, and an increase of 170% is expected between 1970 and 1985. Electricity is an intermediate rather than a basic energy resource; after generation from a primary energy resource, it must be transmitted, and possibly stored, before being converted into useful applications at the final points of use.

This booklet has concentrated on the technology of energy storage, and discussion was concerned largely with electricity. The introduction mentioned that the availability of electrical energy to industry, business, communities, and the average household provides each individual with the equivalent of a large number of servants who can perform hundreds of tasks and a wide variety of services. Where are all these energy trends leading?

There is no simple answer, but in searching for guidelines on which future energy planning can be based, the following facts and figures, however pessimistic, must be squarely faced.

1. The use of the world's natural gas has already peaked, and supplies will be increasingly limited in the future. This natural energy resource, ideal from environmental and other standpoints for a variety of applications, cannot be depended on in the future to supply a large fraction of our domestic supply of energy.

2. The same general situation exists for domestic petroleum supplies that exists for gas, but oil will last longer than

gas. We are already dependent on imported oil for about one-third of our total consumption.

3. Continued dependence on foreign oil and gas, even if this procedure would meet our increasing energy demands, would be almost unthinkable as a long-term national policy. It would not only incur the grave risk of compromising our national security, but would inevitably lead to serious balance-of-payments problems.

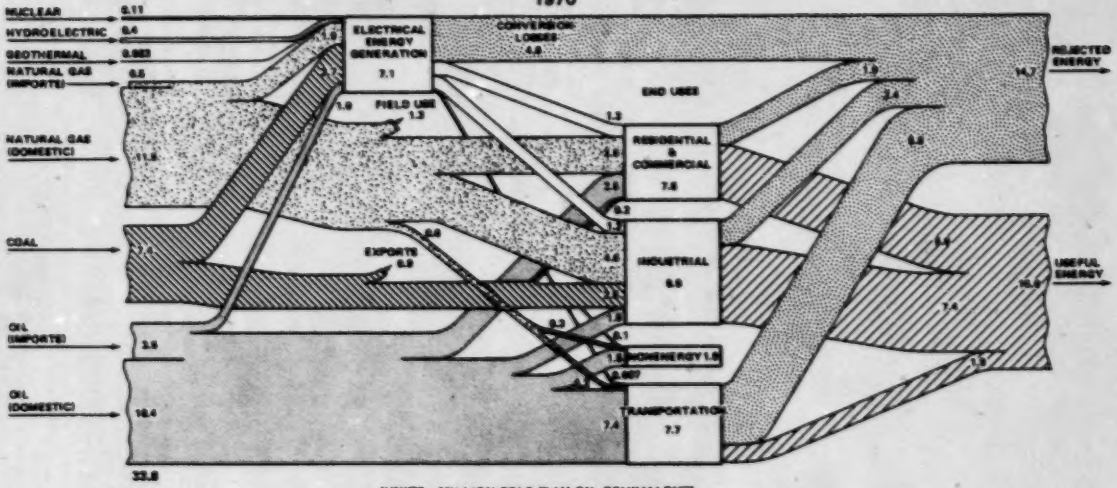
4. The overall situation with regard to coal, while not one of unlimited supplies on earth, is fortunately much more favorable for the immediate future, particularly since the U. S. has close to one-half of the world's coal reserves. It is estimated that there is enough coal in the U. S. to last for several hundred years at current rates of consumption. This would seem to guarantee a substantial amount of coal for the forseeable future even with the continued anticipated increases in consumption. Coal also can be liquefied to produce gasoline or other liquid fuels or gasified for a variety of end-use applications.

5. The availability of energy resources in the longer term depends largely on successful technical developments in three distinct fields: breeder reactors, fusion reactors, and solar electric energy. If breeder reactors (which produce more fuel than they consume) can be successfully introduced in the early 1990s, there will be no shortage of fuel supplies for an indefinite time. If fusion reactors, still in the research stage, become practical, their fuel would be derived from ordinary water, and there would be enough for thousands of years. The fusion principle also has other important advantages, such as better environmental characteristics. Solar electric energy, too, would provide an opportunity to tap the virtually inexhaustible resources of the sun.

6. To date the only significant application of nuclear technology for energy production is the generation of electricity in large central steam-electric plants.

7. Other seemingly inexhaustible energy resources—such as the direct uses of solar energy (i.e., to heat and cool buildings) and geothermal energy—are useful for many applications. Although they cannot completely solve our

U. S. ENERGY FLOW
1970



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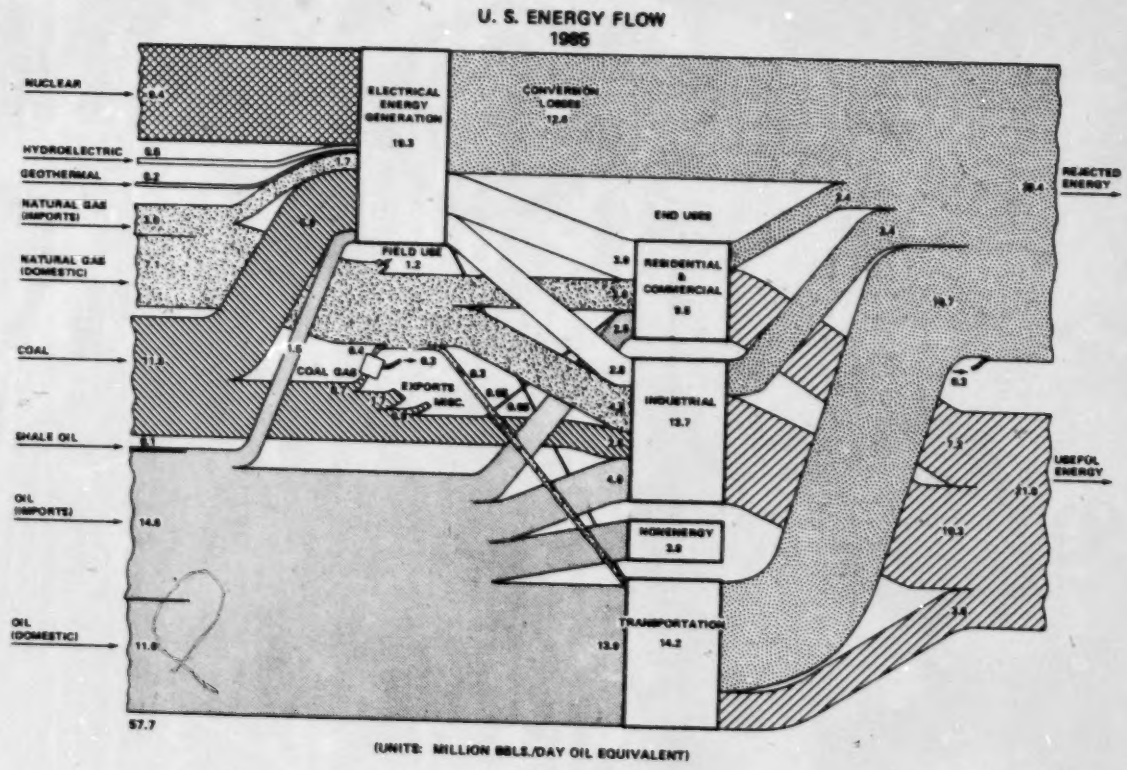
U. S. ENERGY FLOW
1985
NUCLEAR
8.4
HYDROELECTRIC
0.6
GEOTHERMAL
0.2
NATURAL GAS (IMPORTS)
3.0
NATURAL GAS (DOMESTIC)
COAL
SHALE OIL
0.1
OIL (IMPORTS)
14.6
OIL (DOMESTIC)
11.0
57.7
ELECTRICAL ENERGY GENERATION
19.3
CONVERSION LOSSES
12.6
FIELD USE
1.2
COAL GAS
EXPORTS
MISC.
END USES
RESIDENTIAL & COMMERCIAL
9.8
INDUSTRIAL
13.7
NONENERGY
2.8
TRANSPORTATION
14.2
REJECTED ENERGY
30.4
USEFUL ENERGY
27.3
(UNITS: MILLION BBLS./DAY OIL EQUIVALENT)

energy problems, they can provide useful supplementary sources of energy in the midterm and long-term.

Problems of oil and gas supplies, together with the growth of nuclear power and a revival of coal, could lead to a very substantial increase in the already evident trend of relying more and more on electricity. This type of electrically oriented society has often been called the "electric economy" of the future.

The signs of such an electric economy begin to be more and more evident. The fraction of total energy used to generate electricity will probably rise from the present value of one-quarter to the one-third indicated in the 1985 graph in the figure and up to one-half by the year 2000.

As these trends continue, the need for developing much better techniques for storing electricity (or energy that can readily be converted to electricity) becomes correspondingly more urgent. Success achieved in surmounting technical problems will be important in determining whether the generation and use of hydrogen is needed, as outlined in Chapter II, and this may lead to a kind of alternative concept—the "hydrogen economy".

The "electric economy" and the "hydrogen economy" are two broad concepts that are not necessarily entirely separate and distinct from one another. It could easily turn out, depending upon how various technologies develop, that there will be an overlapping situation where both hydrogen and electricity would be used in various applications for which they would be individually best suited.

Perhaps such a combination will eventually emerge as the most appropriate and effective way to match the available supplies of energy on earth to the needs of mankind. Availability of electrical power will be an important factor in assisting the developing countries of the earth in their continuing struggles to improve the conditions of their existence.

This is why the "electric economy", and its possible combination with the "hydrogen economy", is important, and why advancements in the technology of energy storage are so vital. Research and development efforts in these fields,

financed either by industry or by Government appropriations, may be investments with a high payoff and long-term significance for our country.

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